New Method for Characterizing the Injected-carrier-to-photon Conversion Efficiencies Inside the Ultrafast all-optical Semiconductor Gates

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Abstract:
We propose a new method to characterize the conversion efficiency from the injected carriers to the excess photons in the process of all-optical gating in SOA, and investigated the efficiencies of SOAs with different structures.
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OCIS codes: (250.5980) Semiconductor optical amplifiers;   (190.5970) Semiconductor nonlinear optics including MQW;

1   Introduction

Semiconductor Optical Amplifiers (SOAs) are expected to perform essential function in future OTDM-WDM networks acting as ultrafast nonlinear optical devices. Demonstrations of all-optical demultiplexing, 3R regeneration and wavelength conversion using SOA-based all-optical gates have been reported for operation bit rates exceeding 100 Gbit/s[1-3]. As their capability of ultrafast gating has become clear, the lower limit of electric power consumption and its origin have been important issues from a physical and design viewpoint. When we use an SOA for optical gating, we must inject carriers into its active region at the cost of some electric power. Then population inversion is achieved, and we can cause stimulated emission, carrier recombination and gain/phase modulation by injecting cw or pulsed light. We have speculated, however, that there are several loss processes for the injected carriers, and only a part of them can be converted to photons through the stimulated emission. Then the conversion efficiency in each loss process will determine the required amount of power consumption. As far as we know, no method to evaluate these conversion efficiencies has been studied for SOA in an ultrafast operation. Therefore we propose a new characterization method of these efficiencies, and report measured results on several SOA samples with different chip-lengths and structures. This is our first step to find the way to fabricate an SOA with low power consumption.

(a) Injection current I_{op}

η_1

(Current at transparency, I_0)

(b) Current over transparent condition, $I_{op}-I_0$

η_2

[ASE emission, carrier overflow, Auger recombination]

(c) carriers which contribute to cw light amplification

η_3

(hole burning, increase in ASE, overflow, etc.)

(d) carriers which contribute to pulse light amplification
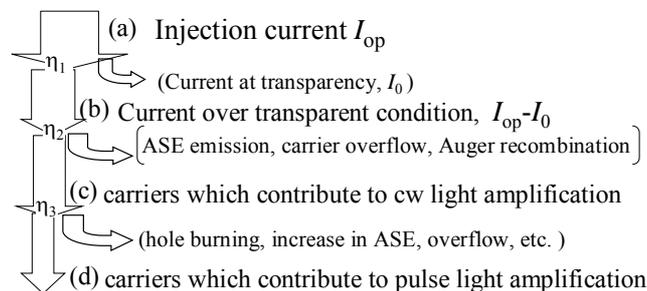
Figure 1. Loss model of the injected carriers and definition of the conversion efficiency

2   Definition of carrier conversion efficiency in this work

In this section we define the carrier conversion efficiencies, which will be used for the evaluation of the carrier losses in the SOA. Our loss model of the injected carrier is summarized in Fig. 1. The SOA stores carriers $N(I_{op})$ in its active region with the injection of a driving current I_{op}. When I_{op} exceeds the transparent current I_0, (and N exceeds N_0,)

population inversion occurs and the SOA has a positive gain $G(N)>1$. Thus we define $\eta_1 \equiv (I_{op}-I_0)/I_{op}$ a current ratio which exceeds transparent current. Then the total number of the excess carriers, i.e. $N^{ex} \equiv N-N_0$, can be approximately given as follows: In many applications, carrier dynamics in the SOA is well described with a rate equation model[4];

$$\frac{d}{dt}\overline{n_c(t)} = \frac{\overline{I_{op}}}{qV} - \frac{\overline{n_c(t)}}{\tau_c} - \frac{1}{V} \cdot \{G[\overline{n_c(t)}]-1\} \cdot \frac{|E_{CW}|^2 + |E_{pulse}(t)|^2}{\hbar\omega}. \tag{1}$$

Where n_c stands for the carrier density averaged over the whole length of the active region (with volume V), q represents the elemental charge, E_{cw} and E_{pulse} are the amplitudes of the input lights and τ_c is the carrier lifetime. When there is no input light, equation (1) has a steady solution. Then the excess carrier number N^{ex} is given by

$$N^{ex}_{injection} = \frac{I_{op}-I_0}{q} \times \tau_c. \tag{2}$$

We define this quantity as the nominal injection carrier number.

Apart from the estimation from current injection, we can estimate carrier densities from amplification of a cw light or ultrafast pulses in the SOA. If there are N_{cw} carriers which contribute to the cw amplification, N_{cw} should be related to the saturation power $P_{sat}{}^{cw}$, the carrier lifetime τ_c and the small signal gain (SSG) G_0[4,5]. Similarly, if there are N_{pulse} carriers which contribute to the pulse amplification, the saturation energy $E_{sat}{}^{pulse}$ should be determined by them;

$$N_{cw} = \frac{P_{sat}^{cw}}{h\nu} \times \ln G_0 \times \tau_c, \tag{3}$$

$$N_{pulse} = \frac{E_{sat}^{pulse}}{h\nu} \times \ln G_0. \tag{4}$$

As illustrated in Fig. 1, we assume that N_{cw} is smaller than $N^{ex}_{injection}$ due to ASE emission, carrier overflow, Auger recombination *etc.*, and that N_{pulse} is smaller than N_{cw} due to spectral hole-burning *etc.* Then $\eta_2 \equiv N_{cw}/N^{ex}_{injection}$ and $\eta_3 \equiv N_{pulse}/N_{cw}$ represent the efficiencies in these loss processes.

For the ultrafast all-optical gating it is important to achieve large N_{pulse}. That is realized when the total conversion efficiency $\eta \equiv \eta_1\eta_2\eta_3$ is maximized. It will be possible by improving each contribution separately, once their dominant factors are revealed.

3   Conversion efficiency measurement and results

To demonstrate the validity and utility of the former model, we performed SOA-parameter measurements and deduced carrier conversion efficiencies. So far we have measured seven SOA samples, as summarized in Table 1, to observe SOA-structure dependence. Two samples (K#1 and K#2) were designed by us and had similar cross-sectional structures with each other. The rest were commercial modules or custom chips by other manufacturers.

To obtain ultrafast optical pulses with lower frequency than carrier-recovery rates of the SOAs, we used a mode-locked fiber laser (MLFL: Pritel Inc., UOC-3) with a LiNbO$_3$ modulator. Pulses with 2-ps width, λ=1555 nm and 10.5-GHz frequency from the MLFL were modulated down to 0.65-GHz or 1.3-GHz pulse train with the extinction ratio of typically 20 dB. The carrier lifetimes for several injection currents were acquired through cross gain modulation measurements, using a cross-correlator (Femtochrome Research Inc., FR-103XR). CW light (λ=1548 nm, -10 ~ -20 dBm) from a DFB-LD was gain-modulated in the SOA by the low-frequency pulses. By assuming that the gain recovery profile $G(t)$ is proportional to $\exp(g(N(t)-N_0))$, we obtained the carrier lifetimes τ_c. Gain saturation and SSG for cw input and also for pulse input were measured using same light sources and spectrum analyzers. The measured result of pulse-gain saturation for K#1 sample is shown in Fig. 2 as an example. The saturation energy E_{sat} for the ultrafast pulses was obtained by fitting to the theoretical gain saturation formula[5]. The saturation power P_{sat} for the cw light was obtained from cw output power at 3-dB gain suppression, by $P_{sat} = P_{3dB}/\ln 2$ [5].

Then the three kinds of excess carrier numbers N and densities n_c were obtained from those parameters. The results for two SOA samples are shown in Fig. 3. We observed that the measured carrier densities for all the SOA samples followed the relation: $n^{ex}_{injection} > n_{cw} > n_{pulse}$. This fact supports our carrier-loss model in Fig. 1.
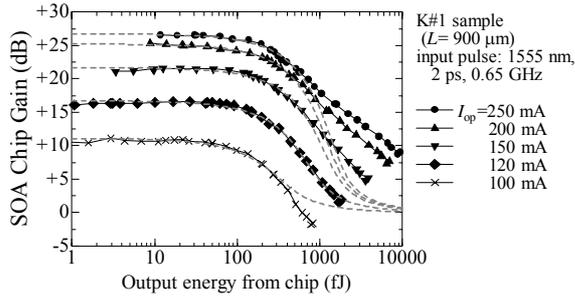
Figure 2: Example of measured gain saturation for pulse amplification. Dashed lines are fit curves.
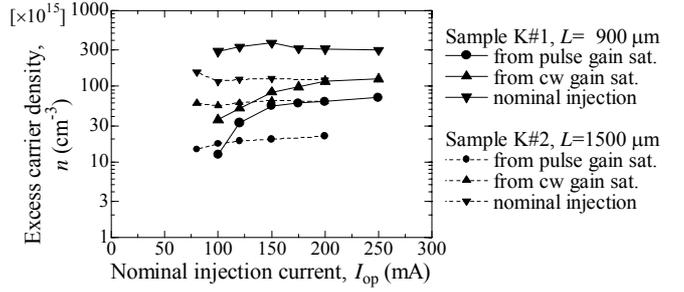
Figure 3: Measured results of the carrier densities at each stage in the Fig.1. $n^{ex}_{\text{injection}}$: Fig.1(b), n_{cw}: Fig. 1(c), n_{pulse}:Fig. 1(d)

Table 1: list of the SOA samples

Sample	Description	Active Region Length (μm)	Symbol
K#1	custom	900	- ▼ - -
K#2	custom	1500	- ▲ - -
Av#1	Avanex Inc., A1901	700	- ● -
In#1	InPhenix Inc., custom chip	300	- □ -
In#2	InPhenix Inc., custom chip	700	- + -
In#3	InPhenix Inc., custom chip	1000	- ✕ -
In#4	InPhenix Inc., IPSAD1501	700	- ⊙ -
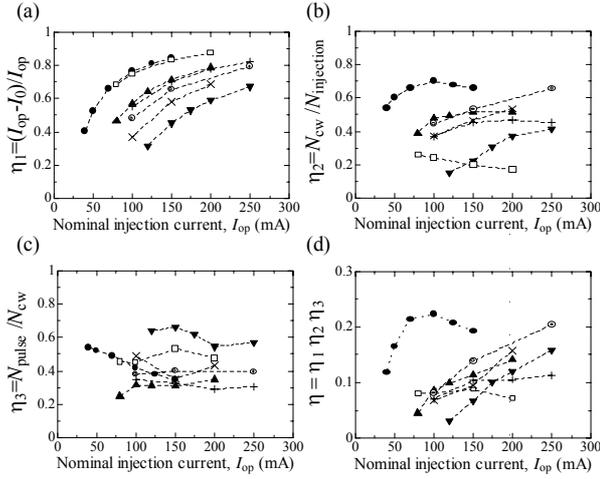
Figure 4: measured carrier-conversion efficiencies for each SOA samples.
(a), (b), (c): each efficiencies η_1~η_3 and (d): total efficiency

The conversion efficiencies in each of the loss processes are shown in Fig. 4. The total efficiencies η of these SOA for the ultrafast gating use were around 0.1~0.2. These results indicate that the total efficiency is not quite sensitive to the chip length, while largest η_3 and smallest η_2 were obtained with shortest samples in the set of simillar cross-sectional structure. In our next plan of surveying SOA series with different structures, we will search for the dominant factors for each efficiency and more efficient SOA structures.

4 Conclusion

We developed a new technique to characterize the conversion efficiencies of injected carriers into the carriers used in the ultrafast gating. This method was applied to SOA samples with different chip-lengths and structures. The results support our carrier-loss model. The conversion efficiency obtained in this work ranged from 0.1 to 0.2. Our on-going research with this technique will provide a way to design and fabricate highly efficient SOA.

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